United States Patent Application for:

MONITORING A PROCESS AND

COMPENSATING FOR RADIATION SOURCE FLUCTUATIONS

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MONITORING A PROCESS AND
COMPENSATING FOR RADIATION SOURCE FLUCTUATIONS

BACKGROUND

The present invention relates to monitoring of a substrate fabrication process.

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In the fabrication of electronic devices, semiconductor, dielectric and conductor materials, such as for example, polysilicon, silicon dioxide, and metal containing layers, are deposited on a substrate and etched to form features such as patterns of gates, vias, contact holes and interconnect lines. These features are typically formed by chemical vapor deposition (CVD), physical vapor deposition (PVD), oxidation and etching processes. For example, in a typical etching process, a patterned mask of photoresist or oxide hard mask is formed on a substrate by photolithographic methods and exposed portions of the substrate are etched by a plasma. In a typical CVD process, a plasma of a gas is decomposed to deposit a layer on the substrate. In PVD processes, a target facing the substrate is sputtered to deposit the target material onto the substrate.

In such processes, it is often necessary to monitor events within the process chamber, including process conditions such as pressure, temperature, deposition on chamber sidewalls, and especially substrate characteristics such as etch depth, layer thickness and composition. For example, in deposition processes, it may be desirable to change process conditions to change the nature of the film being deposited on the substrate or to stop deposition after a desired film thickness has been obtained. In etching processes, it may be desirable to stop etching of a particular layer (for example, a gate oxide layer) at a specified thickness. Techniques to monitor substrate characteristics involve providing radiation in the process chamber to interact with the substrate and/or a plasma and detecting the radiation emanating from the chamber. Chamber conditions such as the thickness of deposits formed on chamber walls, can also be monitored by directing the radiation onto the chamber wall and measuring the reflected radiation.

Examples of these monitoring techniques include interferometry and ellipsometry. In interferometry, a light beam directed onto a layer on a substrate is partially reflected from the surface of the layer, and partially transmitted through the layer and reflected by one or more underlayers. Constructive and destructive

5   interference of the multiple reflections give rise to an interference pattern which undergoes periodic maxima and minima depending upon the path length of the radiation through the thickness of the layer being processed on the substrate. Before processing of the substrate, an initial thickness of the layer is assumed or measured. During processing, the observed periodic maxima and minima of a measured

10   interference pattern are directly correlated to a calculated reduction in thickness of the layer (which would result in a changing pathlength of the radiation transmitted through the layer being processed) to estimate an endpoint of the process. Examples of interferometric apparatus and techniques are described in U.S. Patent Nos. 4,776,695, 5,691,540, 4,680,084, 4,840,487, and 5,087,121 – all of which are

15   incorporated herein by reference. As another example, in ellipsometry, a polarized light beam is reflected from a layer being processed on a substrate and analyzed to determine changes in the phase and magnitude of the reflected light beam that occur as the layer is being processed, as for example as disclosed in U.S. Patent Nos. 3,874,797 and 3,824,017, both of which are incorporated herein by reference.

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In the processing of sub-micron sized features, the magnitude of the radiation signal used to monitor the processing of features on the substrate becomes proportionately smaller as the size of the features becomes smaller. As a result, the signal-to-noise ratio of the monitored signal is significantly reduced and any

25   fluctuations of the light sources from which the radiation signals originate, play a larger role in reducing the radiation signal being monitored. In prior art processes, the small levels of the source fluctuations were not a significant problem because process-induced changes in the reflected radiation had a relatively large magnitude. However, as the size of the etched features or the thickness of the etched and

30   deposited layers becomes smaller, the magnitude of the reflected radiation change is also smaller, and previously undetectable signal fluctuations now reduce the signal to noise ratio to unacceptably low levels.

In addition, radiation generated from the plasma may also interf re with the radiation signal that is being monitored during the process, which further reduces the signal to noise ratio of the monitored radiation signal. When an external radiation source is used as the source of the radiation, the background radiation from the plasma interferes with, or dominates, the radiation measurements that are being monitored, especially where the radiation being measured has wavelengths similar to the radiation emitted by the plasma. This overlap of wavelengths occurs, for example, where a mercury lamp is used as the radiation source, and a silicon dioxide or other dielectric layer is being etched with a plasma containing fluorine or argon. In these cases, it is desirable to reduce the effect of the fluctuations of background and the source radiation.

Thus, it is desirable to accurately monitor radiation signals during the plasma processing of a substrate in a process chamber. It is further desirable to reduce signal fluctuations that occur during processing and improve the signal-to-noise ratio of the radiation measurements. It is also desirable to have a process chamber and monitoring system that may be easily adapted to existing apparatus.

SUMMARY

These needs are satisfied by the present invention. In one aspect, the invention provides a substrate processing apparatus comprising a process chamber, a radiation source capable of providing radiation in the chamber; one or more detectors to detect a first radiation from the chamber and a second radiation from the radiation source; and a signal analyzer to normalize a property of the first radiation relative to a property of the second radiation.

In another aspect, a method for monitoring processing of a substrate in a chamber comprises the steps of providing radiation in the chamber, detecting the radiation after it interacts with the substrate being processed, and generating a sample signal detecting a reference radiation that does not interact with the substrate and generating an reference signal; and normalizing the sample signal relative to the reference signal.

In a further aspect, a substrate processing apparatus comprises a chamber capable of processing a substrate. The chamber comprises a radiation source. A detector is provided to detect a reflected radiation from the chamber and to generate a sample signal. A signal analyzer is adapted to receive the sample signal and to determine a corrected sample signal, X_{nt}, using the expression $X_{nt} = X_t / \{Y_0 + C(Y_t - Y_0)\}$, where C is the correction factor, Y_0 is the reference signal at time 0, X_t is the sample signal at time t, and Y_t is the reference signal at time t.

In another aspect, a substrate processing apparatus comprises a chamber capable of processing a substrate. The chamber comprises a radiation source. A sample detector is provided to detect a reflected radiation from the chamber and to generate a sample signal. A reference detector is provided to detect a reference radiation from the radiation source and generate a reference signal and one or more first fibers are provided to transmit the reference radiation to the reference detector.

In yet another aspect, a substrate processing apparatus comprising a chamber capable of processing a substrate. The chamber comprises a radiation source that includes a plasma; a sample detector to detect a reflected radiation from a substrate in the chamber and generate a sample signal; a reference detector to detect a reference radiation from the plasma and generate a reference signal; and one or more first fibers to transmit the reference radiation to the reference detector.

In another aspect, a substrate processing apparatus comprises a chamber having a radiation source; a detector to detect a property of a radiation from a radiation source; and a feedback controller to regulate a power level of the radiation source in relation to the detected property of the radiation.

In another aspect, a substrate processing apparatus comprises a chamber; a radiation source; a detector to detect a property of a radiation from a radiation source and generate a reference signal; and a radiation modulator in a path of a radiation being transmitted from the radiation source to the chamber, whereby the radiation modulator may receive a signal from the radiation source and control a property of the radiation in relation to the reference signal.

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In a further another aspect, a method for monitoring processing of a substrate in a chamber comprises the steps of providing radiation in the chamber; detecting a reference radiation that does not interact with the substrate and generating an reference signal; and controlling a property of the radiation in relation to the reference signal.

DRAWINGS

These and other features, aspects, and advantages of the present invention will be better understood from the following drawings, description and appended claims, which illustrate examples of the invention. While the description and drawings below illustrate exemplary features of the invention, it is to be understood that each of the features can be used in the invention in general, not merely in the context of the particular drawing, and the invention includes any combination of these features.

Figure 1 is a schematic sectional view of a substrate processing apparatus according to the principles of the present invention;

Figures 2a to 2d are schematic diagrams showing different arrangements of fiber bundles for receiving source or reference radiation;

Figure 3 is a flowchart of a process for monitoring etching of a substrate in the apparatus of Figure 1;

Figure 4 is a graph of the intensities versus time of a sample signal (a), the corresponding reference signal (b), and the normalized sample signal after correcting for fluctuations in source and background radiation (c);

Figure 5 is an illustrative block diagram of a hierarchical structure of a process control software of a computer-readable program according to the present invention; and

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Figures 6 and 7 are schematic diagrams of an apparatus suitable for compensating for source fluctuations by a feedback loop circuitry.

DESCRIPTION

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The present invention is useful for monitoring events in an apparatus via a radiation measuring technique such as for example, reflectance/absorbence, interferometry, ellipsometry and photoluminescence. The events are process characteristics that include for example, process conditions such as pressure,
10 temperature, deposition on chamber sidewalls; and substrate properties such as etch depth, layer thickness, trench depth and composition. The invention is particularly useful for endpoint detection and reflectivity-based processes, such as interferometry, that are conducting during plasma etching or deposition processes. For example, a substrate **20** may be etched in the etching apparatus **26** that is illustrated in Figure 1,
15 and the etching process being conducted on the substrate **20** may be monitored by the present invention. Typically, the substrate **20** comprises a support, such as a wafer of silicon or a compound semiconductor, or a dielectric such as silicon dioxide, and the substrate **20** may have thereon a plurality of layers, such as for example, It ~~include~~ dielectric, semiconducting, and metal-containing conductor layers. Generally,
20 the apparatus **26** comprises a process chamber **28** having a process zone **30** for processing the substrate **20** and a support **32** that supports the substrate **20**. Process gas is introduced into the chamber **28** through a gas delivery system **34** comprising a process gas supply **36**, gas outlets **38** located around the periphery of the substrate **20** (as shown) or in a showerhead mounted on the ceiling of the
25 chamber (not shown), and a gas flow controller **40** adapted to control the flow rate of the process gas. Spent process gas and etchant byproducts are exhausted from the chamber **28** through an exhaust **42** comprising roughing and turbomolecular pumps (not shown) and a throttle valve **44** is used to control the pressure of process gas in the chamber **28**. An energized gas or plasma is generated from the process gas by a
30 plasma generator **46** that couples RF or microwave energy to the process gas in the process zone **30** of the chamber **28**, such as for example, an inductor antenna **48** comprising one or more coils powered by an antenna power supply **49** that inductively couple RF energy to the chamber. In addition, a first process electrode **50** – such as an electrically grounded ceiling or sidewall of the chamber **28**, and a second electrode

52 – such as an RF biased support 32 below the substrate 20, can be used to further energize the gas in the chamber 28. The first and second electrodes 50, 52 are electrically biased relative to one another by an RF voltage provided by an electrode voltage supply 54. The frequency of the RF voltage applied to the inductor antenna

5   48 and the electrodes 50, 52 is typically from about 50 KHz to about 60 MHz and more typically about 13.56 MHz.

The apparatus also comprises a radiation source 58 that may be outside or inside the chamber to provide a source of radiation in the chamber 28. The

10   radiation source 58 may comprise, for example, an emission from a plasma generated inside the chamber 28, the plasma emission being generally multispectral, i.e., providing radiation having multiple wavelengths extending across a spectrum. The radiation source 58 may also be positioned outside the chamber 28 so that radiation 60 is passed from the source 58 through a window 61 and into the chamber 28. The

15   radiation source 58 may provide radiation such as ultraviolet (UV), visible or infrared radiation; or may provide other types of radiation such as X-rays. In one version, the radiation source 58 provides radiation having only a predominant wavelength, such as a monochromatic light having primarily radiation at a single or a few wavelengths, for example, a He-Ne or Nd-YAG laser. Alternatively, the radiation source 58 may

20   provide multiple wavelengths of radiation, such as polychromatic light, which may be selectively filtered to provide substantially only a single wavelength. Suitable radiation sources 58 for providing polychromatic light include Hg discharge lamps that generate a polychromatic spectrum of light having wavelengths in the range of from about 180 to about 600 nanometers, arc lamps such as xenon or Hg-Xe lamps and tungsten-

25   halogen lamps; and light emitting diodes (LED).

During process monitoring, it has been discovered that instabilities of the properties or other characteristics of the radiation emitted from the radiation source 58 can significantly reduce the signal to noise ratio of the monitored or detected

30   radiation. These instabilities may be in the form of changes in the intensity, wavelength or phase of the radiation. For example, UV lamps have been found to exhibit substantial intensity instabilities of emitted UV radiation during the time it takes to fully process a substrate. From a study of mercury arc lamps it has been further discovered that the intensity of these lamps may vary temporally as a function

of time, spatially with different areas of the lamp emitting different intensities, or both temporally and spatially, and the temporal variations may also differ at differing wavelengths. The instabilities may include spikes, jumps and broadband noise. In a series of experiments, the intensity of low-pressure discharge mercury lamps was

5 measured over several days using a UV-sensitive PMT detector with a bandpass filter. The lamp intensity was observed to oscillate intermittently over a duration of minutes, hours and even days with an amplitude of up to 5% and a period of 3 to 90 seconds. Similar instabilities can be observed for other sources such as arc lamps. The instabilities are not predictable, may occur for only a few seconds or a few hours and

10 may result in significantly inaccurate measurements, especially when the feature being measured is thin or small. Thus it is important to correct the lamp instabilities in situ with processing of the substrate.

The system **56** further comprises a first radiation detector **62** which serves as a sample detector for detecting radiation **64** emanating from the chamber

15 **28** and after the radiation is reflected from the chamber walls or substrate **20**. A single radiation detector **62** may be used to detect both the reflected radiation as well as radiation originating directly from the radiation source **58**, by for example, alternating inputs from the source **58** and process chamber **28**. Alternatively, the system **56** may also comprise a plurality of detectors, including for example a second

20 radiation detector **63** which serves as a reference detector for detecting radiation emitted from the radiation source **58**. The detectors **62**, **63** comprise a radiation sensor, such as a photovoltaic cell, photodiode, photomultiplier, or phototransistor, which provides an electrical output signal in response to a measured intensity of the

25 sample radiation **64**. The detector signal can comprise a change in the level of a current passing through an electrical component or a change in a voltage applied across an electrical component. The detector may comprise a photomultiplier (PMT), such as those commercially available from Hamamatsu, Japan.

30 The detectors **62**, **63** may be coupled to the chamber **28** by one or more radiation transmitting fibers **69** or other equivalent means for transmitting radiation, such as a radiation conduit, that lead from the chamber **28** to the detectors **62**, **63**. This reduces noise from the external environment by providing an isolated radiation pathway along which the radiation is carried. The type of fiber **69** depends upon the

radiation being transmitted therethrough, for example, an optical fiber is suitable for the transmission of UV or visible radiation. In one version, the fibers **69** comprise one or more sets or bundles of fibers, as shown in Figure 1, with for example, one fiber bundle **69a** being used to transmit radiation emanating from the chamber **28** to a

5   sample detector **62** that measures the radiation properties during processing of a substrate **20** in the chamber **28**. Another bundle of fibers **69b** is positioned so that one end **71a** receives radiation directly from the radiation source **58**, and the other two bifurcated ends **71b,c** transmit the radiation to a reference detector **63** and to the chamber **28**, respectively. This arrangement of fibers is suitable for transmitting

10   radiation directly from the source **58** to the chamber and detectors to allow for correction of temporal variations in the properties of the radiation provided by the source, i.e., when a property of the radiation varies over a period of time.

Effective use of ratio mode depends on a sampling method if light intensity varies spatially as well as temporally. Thus, when using a beam splitter or

15   pick-off mirror, the area of the source **58** that is sampled for the reference detector **63** must correspond as closely as possible to that of the area of the source **58** that is sampled to serve as the radiation for the chamber **28b**. For example, in the version shown in Figure 2a, a pair of fibers **69c,d** are shown with their ends **71d,e** provided

20   adjacent to the radiation source **58** to receive radiation therefrom, and with their other ends **71f,g** transmitting the radiation to the chamber **28** and the reference detector **63**, respectively. Fiber sampling has an intrinsic advantage due to the small size of the fibers **69c,d**. If the size of the fibers **69c,d** is much larger than the area of the source **58** being sampled, then side-by-side fibers, one for the signal beam to the

25   chamber **28** and one for the reference beam, may be used to sample the same area of the source **58** to provide good cancellation of source fluctuations. The conical fields of view **73a**, **73b** for each of the fibers **69c,d**, respectively, are positioned so that they have a substantially overlapping field of view of the same spatial area of radiation being emitted from the radiation source **58**. This ensures that both ends **71d,e** of the

30   fibers **69c,d** see the same radiation and compensate for both spatial and temporal variations in the properties of the radiation emanating from the source **58**. Thus, if there are spatial variations in the property of the radiation, i.e., variations that occur across the area of radiation emitted from the source **58**, this arrangement allows both

fibers **69c,d** to see the same variation, thereby allowing for compensation of such variations.

If the area of the fibers **69** is large because a bundle is used, then the

5   fibers that are used to collect radiation for the reference detector **63** are in the signal bundle, and may be evenly distributed within the bundle or at the center of the bundle if only a few fibers are used. For example, in the version illustrated in Figure 2b, two sets of fibers **69g,h** are spaced apart and distributed so that the radiation seen by each set is from substantially the same sized area of the radiation source **58**, which

10   may be a portion or the entire field of radiation emanating from the source **58**. For example, the fibers **69g** that transmit radiation from the source **58** to the reference detector **63** may be interspersed with the fibers **69h** that transmit radiation from the source **58** to the chamber **28** so the conical fields of view **73c,d**, respectively, cover an entire radiation transmitting portion of the radiation source. The larger area of the

15   source **58** covered by a plurality of fibers having overlapping field of views **73c,d** reduces the spatial variability of the radiation and allows averaging of the radiation signal emanating from a larger portion or area of the radiation source **58**. It may also be desirable for both sets of fibers **69g,h** to cover the same area of the radiation source **58** so that the same source fluctuations are seen, and this is

20   accomplished by interspersing the fibers to provide overlapping fields of view covering the same region.

In the version illustrated in Figure 2c, a lens **77** (or lens assembly which is not shown) is used to focus radiation from the radiation source **58** onto an end

25   **73** of the fibers **69**. The lens **77** can match the field of view of the fibers **69** thereby allowing more radiation to be incident on the fibers and is particularly useful when the area of the end **73** of the fibers **69** is much smaller than the radiation emitting area of the radiation source **58**. Again, because a larger area of radiation from the source **58** is concentrated and focused onto the end of the fibers **69**, there is provided

30   enhanced averaging of the spatial variations of the radiation emanating from the radiation source **58**, thereby further reducing the effect of such variations. Alternatively, the lens **77** can be used to couple light from a selected region of the radiation source if that region is more stable.

Figure 2d illustrates simply that the radiation source **58** may also be the plasma in the chamber **28** that emits radiation, and when such a source is used the fibers **69e,f** are positioned to receive the reflected radiation **64** from the substrate **20**, as well as reference radiation **62** which is not reflected from the substrate **20** and

5   originates directly from the plasma in the chamber **28**. For example, the fibers **69e** are positioned to transmit reflected radiation **64** from the substrate **20** directly to the sample detector **62**; and the fibers **69f** transmit radiation from a portion of the plasma which is not reflected from the substrate -- by being pointed toward another region such as a wall **50** in the chamber **28** - to the reference detector **63a**. In

10   another embodiment, the reference detector **63b** also receives radiation **62b** originating from the plasma but which is viewed from the side of the plasma (which does not interact with the substrate) and not from the top of the plasma (which does interact with the substrate). In these versions, the fluctuations in plasma intensity that arise from species emission charges, plasma brightness variations, or

15   other such variations, are needed to compensate for the fluctuation and are detected by collecting plasma light which is not reflected off the substrate **20**.

In these versions, the fibers **69** may preferably lead directly to the reference detector **63** so that the radiation pathway travels along the fiber to the reference detector **63** substantially without ending or breaking in the process chamber

20   **28** and without ending or breaking for moving parts (although the radiation may pass through a nonmoving filter). This direct connection via the fiber **69** is less prone to collect noise from outside light sources and easy to configure in different types of apparatuses. Thus, the directly connected fibers **69** are advantageous over other light

25   transmitting systems employing either moving parts (such as monochromators) or more complex parts (such as conventional beam splitters). However, the fibers **69** may be replaced by a beam splitter (not shown) such as a semipermeable mirror to transmit a reference signal to a detector **63**. While the beam splitter will work, it is generally preferred to use fibers **69** to transmit radiation originating from the radiation

30   source **58** directly to the detector **63**. This is because conventional beam splitters are more costly and complex and require additional mounting and positioning means. Also, although a conventional beam splitter works well with a well-defined and collimated beam with a consistent profile, if the intensity of the radiation from the

source 58 varies spatially, the portion of the beam which acts as a reference must be selected by additional optics and such means.

Optionally, a lens 66 (or assembly of lenses) is used to focus radiation emitted by the radiation source 58 onto the substrate 20 and/or to focus radiation 64 at least partially reflected back from the substrate 20 onto the sensor of the detector 62. For example, for a radiation source 58 comprising a Hg-discharge lamp located outside the chamber 28, as shown in Figure 1, a plurality of convex lenses 68a, 68b can be used to focus radiation from the lamp through the window 61 and onto a beam spot 70 on the substrate 20. The area of the beam spot 70 should be sufficiently large to provide an accurate measurement of the surface topography of the substrate 20. The lenses 68a, 68b can also be used to focus reflected radiation 64 back onto the sensor of the radiation detector 62. The configuration in which radiation strikes the substrate at an incident angle of about 90°, as shown in Figure 1, is preferred for interferometry; however, as is known in the art, other incident angles can also be used and the apparatus 26 for receiving the reflected radiation positioned accordingly.

Optionally, a positioner 72 is used to scan the incident radiation 60 across the substrate surface to locate a suitable portion of the substrate 20 on which to "park" the beam spot 70. The positioner 72 comprises one or more primary mirrors 74 that rotate at small angles to deflect radiation from the radiation source 58 onto different positions of the substrate surface (as shown). Alternatively, the mirrors 74 can also direct radiation emitted from a plasma emission and at least partially reflected off the substrate 20 back onto the radiation detector 62. Additional secondary mirrors (not shown) can be used to intercept and focus reflected radiation back on the radiation detector 62. The positioner 72 can also be used to scan the radiation in a raster pattern across the substrate 20. In this version, the positioner 72 further comprises a movable stage (not shown) upon which the radiation source 58, lens assembly 66, and radiation detector 62 are mounted. The movable stage can be moved through set intervals by a drive mechanism, such as a stepper motor, that scans or otherwise moves the beam spot 70 across the substrate 20.

Radiation having a plurality of wavelengths, such as polychromatic light from a lamp or a plasma emission spectra, can be reduced to a single or narrow band of wavelengths by placing a monochromator or filter 75, 76 in the path of the radiation detector 63 and/or the incident or reflected radiation 60, 64. The

5   monochromator or filter 76 may be located in the lens assembly 66 but can also be located at other positions in the chamber 28, for example, in the chamber window 61, in front of the radiation detectors 62, 63 or in front of the radiation source 58. A suitable filter comprises a stack of thin films on a transparent support that selectively transmits radiation having the desired wavelength or a lens made from a material that

10   selectively passes radiation having the desired wavelength. The monochromator 75, 76 can also comprise a diffraction grating having a diffraction spacing that scatters radiation having undesirable wavelengths and allow radiation having the desired wavelength to pass through. Although usable in some embodiments, rotating disk monochromators and varying wavelength filters are not preferred because of their

15   greater complexity. For enhanced simplicity and reliability, the monochromator or filter preferably does not have moving parts. Other suitable filtering means, for example, attenuation of radiation through a long pathlength in a partially absorbing material, or selective filtering by the radiation detectors 62, 63 to generate an electrical signal based only the portion radiation having the desired wavelength, can

20   also be used. Since the intensity of the source radiation at different wavelengths can vary independently, it is usually desirable to select for the same wavelength for both the sample and reference radiation.

Properties of the radiation, such as intensity, phase, or wavelength are

25   measured by the radiation detectors 62, 63 and converted to electrical signals. The detectors 62, 63 are capable of detecting a first property of a reflected radiation emanating from the chamber 28 and a second property of the radiation originating from the radiation source 58. The first and second properties can be different properties or the same property. The electrical signals from the detectors 62 (the

30   sample signal) and 63 (the reference signal) are transmitted to a signal analyzer 130 which electrically manipulates or operates on the electrical signals to reduce the effect of the fluctuations in the characteristics of the radiation as it originates from the radiation source 58. For clarity, the signal analyzer 130 and signal monitoring

software **126** are shown as separate components in Figure 1; how ver, these components can be the same thing and are usually part of the computer **114**.

In a first embodiment of the invention, the signal analyzer **130**
5   normalizes a first property of the reflected radiation relative to a second property of the radiation originating from the radiation source **58**. By "normalizing" it is meant that the measured first property of the sample signal is modified by the measured second property of the reference signal to derive a normalized signal that takes into account or has compensated for fluctuations of the source radiation. Thus,
10   normalizing could involve modifying the sample and reference signals by subtraction of one signal from the other, division, or other types of mathematical operations or comparisons, and combinations of these methods. A particular signal normalizing procedure that is found to be especially advantageous for use in semiconductor process chambers, especially plasma chambers, is obtaining a normalized sample
15   signal by dividing the sample signal with the reference signal. The division process of normalization is preferred because it does not require gain matching in the sample and reference channels. In a typical normalization step, the signal analyzer **130** mathematically operates on the sample and reference signals to determine a normalized sample signal by the expression:

$$X_n = X_t / Y_t ;$$

20   where X_n is the normalized sample signal, X_t is the original sample signal at time t, and Y_t is the reference signal also the at same time t. Variations in X_t due to the source will be canceled by the source reference Yt.

25   Even more accurate and less noisy signals can be obtained by accounting for other effects which create differences between the sample and reference signals. Specifically, if the processing environment has radiation which is not from the source (e.g., ambient light), this will add to the sample signal but not to the reference signal. In addition, radiation detectors may have dark current, yielding a
30   nonzero signal when no light is present. Since stray light in the reference channel can be controlled, and detector dark current can be minimized with appropriate choice of detector type and offset electronics, background light in the sample signal channel is typically the dominant factor requiring compensation. During processing in a process chamber **28**, where an external radiation source is used and the corresponding

reflected radiation is used to monitor events in the process chamber, radiation emitted by the plasma is usually the primary source of background radiation. Thus a correction for background radiation can also be applied by the signal analyzer **130** to further reduce the effect of fluctuations in the source and background radiation. The

5 signal analyzer **130** mathematically operates on the sample signals to determine a sample signal corrected for background fluctuations, as shown in equations (1) and (4) below.

In a preferred method, the signal analyzer **130** mathematically operates

10 on the sample and reference signals to determine a normalized sample signal corrected for both source fluctuations and ambient background, using the expression:

$$X_{nt} = X_t / \{Y_0 + C(Y_t - Y_0)\} \qquad (1)$$

where C is the correction factor, Y_0 is the reference signal at time 0, X_t is the sample signal at time t, and Y_t is the reference signal at time t. The correction factor

15 C is determined by:

$$C = \{(X_t - X_1) / X_1 \}\{Y_0 / (Y_t - Y_0)\} \qquad (2)$$

In a process where background radiation is generated (such as plasma processing), the sample signal data point obtained at a time 1 (i.e., at a sufficiently early time when the reflected source signal has not significantly changed from its initial state)

20 can be expressed as:

$$X_1 = X_0 + B_1 \qquad (3)$$

Assuming the background radiation is constant, $B_t = B_1$ for all measurements, i.e., t = 2, 3, etc.

Since the detector gain is constant for small and large signals, the substitution $(X_t -$

25 $X_1) / (Y_t - Y_0) \sim X_0 / Y_0$ can be made, yielding:

$$C = X_0 / X_1 \qquad (4)$$

The system analyzer **130** can use the expression of equation 4 to automatically calculate the correction factor C and apply the correction factor to calculate a normalized sample signal using equation 1. In an alternative embodiment, equation 2

30 rather than equation 4 can be used to calculate the correction factor.

An embodiment of the invention using correction for background light in an etching process may be better understood with reference to the flowchart in Figure 3. Initial measurements of the sample and reference signals are acquired.

Then the plasma is ignited. After the plasma has stabilized, but before significant

etching has taken place, a sample signal, X_1, is acquired and used to calculate the

correction factor C according to equation 4. The etching process is monitored as a

function of time by measuring the sample signal, X_t, and the reference signal, Y_t. The

5   signal analyzer **130** inputs these signals and the correction factor in equation 1 to

calculate the normalized sample signal X_{nt}. In this manner, accurate and reliable etch

measurements are achieved even in the presence of background radiation and source

lamp variations. The normalized sample signal is continuously monitored by the signal

analyzer **130** and/or the computer **114** until the desired etch depth (or, alternatively

10   viewed, layer thickness) has been obtained. This can be either by obtaining a desired

value or desired pattern such as an interference pattern or characteristic endpoint

waveform. At this point, the signal analyzer **130** or the computer **114** relays a signal

to the process controller and the etch process is stopped. Thus etched features

having the desired dimensions or a thickness of a layer deposited on the substrate or

15   in the substrate itself are accurately and reliably obtained. The process may be

monitored and controlled by a human through monitor interface **118** or the process

may be entirely controlled via the automated system **110**.

In another version of the invention, the instability of the radiation source

20   **58** is addressed by monitoring the radiation emitted by the source and using a

feedback controller **87** comprising a conventional closed loop feedback circuit to

control power to the radiation source **58** to regulate any fluctuations or instabilities of

its radiation output. For example, Figures 6 and 7 show two methods to achieve

constant light output using the feedback control method instead of the normalizing

25   mode. Both methods use a reference detector **63** which senses a radiation output or

other property from the radiation source **58**, either directly or using a beam splitter or

fibers **69** as described herein. In the version illustrated in Figure 6, a reference

detector **63** sends a reference signal as feedback to a difference (error) amplifier **79** to

control a programmable power supply **81** which powers the radiation source **58**.

30   When the reference signal deviates from a desired or constant level, an error signal

generated by the feedback controller **87** instructs the power supply **81** to correct in

the direction of reducing the error, to try to maintain the source radiation at a

controlled and flat output level.

Figure 7 illustrates another version of the feedback controller **87**, in which a reference detector **63** is used to control a radiation modulator **83** in the path of the radiation output transmitted to the process chamber **28**. The radiation modulator **83** is a device that modifies or otherwise changes a property of the

5   radiation passing through it. For example, a radiation intensity may be controlled by a radiation modulator **83** comprising a low mass mechanical shutter, mirror, or variable density screen as means for partially attenuating the radiation that moves to block, filter, or otherwise reduce the radiation intensity level from the radiation source **58**. The radiation modulator **83** may also comprise an electro-optical or acoustic-optical

10   transducer that may operate at higher frequencies. Other radiation modulators **83** may also be used which incorporate other elements, such as lenses and diffraction gratings or moving mirrors.

While the feedback controller **87** may be effective in reducing source

15   fluctuations, it may have some disadvantages over the normalizing method. For example, the feedback method may require limiting the nominal radiation output to a lower level than maximum attainable level to enable proper control of source fluctuations. Also, the normalizing method may be preferred for applications requiring as much radiation output as possible to enhance the signal to noise ratio.

20   Other considerations relate to the flexibility and dynamic range that is desirable. For example, as a radiation source **58**, such as a lamp, ages its output decreases over time, the feedback method can only correct over a limited range while the normalizing method can correct over the entire range. In addition, the normalizing method may be less limiting because it may also be used to compensate for background radiation or

25   other effects.

Controller and Computer System

The chamber and endpoint detection system **56** is operated by a

30   chamber controller **110** that executes software of a computer-readable program **112** of a computer system comprising a central processor unit (CPU) **114**, such as for example a 68040 microprocessor, commercially available from Synergy Microsystems, California, or a Pentium Processor commercially available from Intel Corporation, Santa Clara, California, that is coupled to a memory **116** and peripheral computer

components. The memory **116** comprises a computer-readable m dium having a
computer-readable program embodied therein. Preferably, the m mory **116** is a hard
disk drive **122**, but the memory can also be other kinds of memory, such as random
access memory (not shown). In addition to memory **116**, controller **110** can include a
5   floppy disk drive **122** and a card rack. The interface between an operator and the
controller **110** can be, for example, via a monitor **118** and a light pen **120**, as shown
in Figure 1. The light pen **120** detects light emitted by the monitor **118** with a light
sensor in the tip of the light pen **120**. To select a particular screen or function, the
operator touches a designated area of a screen on the monitor **118** and pushes the
10   button on the light pen **120**. Typically, the area touched changes color, or a new
menu is displayed, confirming communication between the user and the controller
110. In the preferred embodiment, two monitors **118** and light pens **120** are used,
one mounted in a clean room for the operators and the other behind the wall for
service technicians. Both monitors **118** simultaneously display the same information,
15   but only one light pen **120** is enabled.

Other computer-readable programs such as those stored on other
memory including, for example, a floppy disk or other computer program product
inserted in a disk drive **122** or other appropriate drive, may also be used to operate
20   the controller **110**. The computer system card rack contains a single-board computer,
analog and digital input/output boards, interface boards, and stepper motor controller
boards. Various components of the apparatus **26** conform to the Versa Modular
European (VME) standard, which defines board, card cage, and connector dimensions
and types. The VME standard also defines the bus structure having a 16-bit data bus
25   and 24-bit address bus.

The computer program **112** generally comprises process control
software **124** comprising a set of instructions of program code to operate the
chamber **28** and its components, signal monitoring software **126**, safety systems
30   software, and other control software. The computer-readable program can be written
in any conventional computer-readable programming language, such as for example,
assembly language, C, C + +, Pascal, or Fortran. Suitable program code is entered
into a single file, or multiple files, using a conventional text editor and stored or
embodied in the computer-usable medium of the memory **116** of the computer

system. If the entered code text is in a high level language, the code is compil d, and the resultant compiler code is th n linked with an object code of precompiled library routines. To execute the linked, compiled object code, the user invokes the object code, causing the CPU 114 to read and execute the code to perform the tasks

5   identified in the program.

The processes for etching the substrate 20 and optionally cleaning the chamber 28 are implemented by the process control software 124 and is executed by the process controller 128. The process control software 124 includes sets of

10   instructions that dictate the timing, gas compositions, gas flow rates, chamber pressure, chamber temperature, RF power levels, support position, heater temperature, and other parameters of a particular process. Figure 5 is an illustrative block diagram of the hierarchical control structure of the process control software 124, according to a specific embodiment. Using a light pen interface, a user enters a

15   process set number and process chamber number into a process selector instruction set 132 in response to menus or screens displayed on the CRT terminal. The process sets are predetermined groups of process parameters necessary to carry out specified processes, and which are identified by predefined set numbers. Process selector instruction set 132 identifies (i) a desired process chamber 28, and (ii) the desired set

20   of process parameters needed to operate the process chamber for performing the desired process. The process parameters for performing a specific process relate to process conditions, without limitations, such as for example, gas composition, gas flow rates, temperature, pressure, plasma conditions such as RF power levels (and in addition, microwave generator power levels for embodiments equipped with remote

25   microwave plasma systems), cooling gas pressure and chamber wall temperature. Process selector instruction set 132 controls what type of process (etching, deposition, wafer cleaning, chamber cleaning, chamber gettering, reflowing) is performed at a certain time in chamber. In some embodiments, there may be more than one process selector instruction set 132. The process parameters are provided

30   to the user in the form of a recipe and may be entered utilizing the light pen and monitor interface.

A process sequencer instruction set 134 comprises program code for accepting the identified process chamber 28 and set of process parameters from the

process selector instruction set **132**, and for controlling operation of the various process chambers. Multiple users can enter process set numbers and process chamber numbers or a single user can enter multiple process set numbers and process chamber numbers, so the sequencer instruction set **134** operates to schedule the

5   selected processes in the desired sequence. Preferably the sequencer instruction set **134** includes program code to perform the steps of (i) monitoring the operation of the process chambers **28** to determine if the chambers are being used, (ii) determining what processes are being carried out in the chambers being used, and (iii) executing the desired process based on availability of a process chamber **28** and the type of

10   process to be carried out. Conventional methods of monitoring the process chambers **28** can be used, such as polling. When scheduling which process is to be executed, sequencer instruction set **134** can be designed to take into consideration the present condition of the process chamber **28** being used in comparison with the desired process conditions for a selected process, or the "age" of each particular user-entered

15   request, or any other relevant factor a system programmer desires to include for determining scheduling priorities.

      Once the sequencer instruction set **134** determines which process chamber **28** and process set combination is going to be executed next, the sequencer instruction set **134** initiates execution of the process set by passing the particular

20   process set parameters to a chamber manager instruction set **136** that controls multiple processing tasks in a process chamber **28** according to the process set determined by the sequencer instruction set **134**. For example, the chamber manager instruction set **136** comprises program code for controlling etch or deposition

25   operations in the process chamber **28**. Chamber manager instruction set **136** also controls execution of various chamber component instruction sets that control operation of the chamber components necessary to carry out the selected process set. Examples of chamber component instruction sets are substrate positioning instruction set, gas flow control instruction set **140**, gas pressure control instruction

30   set **142**, optional heater control instruction set **144** for chambers equipped with a heater in the support, and plasma control instruction set **146**. Depending on the specific configuration of the chamber **28**, some embodiments include all of the above instruction sets or instruction set, while other embodiments may include only some of the instruction sets. Those having ordinary skill in the art would readily recognize that

other chamber control instruction sets can be included depending on what processes are to be performed in the process chamber **28**.

In operation, the chamber manager instruction set **136** selectively schedules or calls the process component instruction sets in accordance with the particular process set being executed. The chamber manager instruction set **136** schedules the process component instruction sets much like the sequencer instruction set schedules which process chamber **28** and process set are to be executed next. Typically, chamber manager instruction set **136** includes steps of monitoring the various chamber components, determining which components need to be operated based on the process parameters for the process set to be executed, and initiating execution of a chamber component instruction set responsive to the monitoring and determining steps.

Operation of chamber component instruction sets will now be described. The substrate positioning instruction set **138** comprises program code for controlling chamber components that are used to load the substrate **20** onto the support **32** and optionally, to lift the substrate **20** to a desired height in the chamber **28** to control the spacing between the substrate **20** and the gas outlets **38** of the gas delivery system **34**.

The process gas control instruction set **140** has program code for controlling the flow rates of different constituents of the process gas. The process gas control instruction set **140** controls the open/close position of the safety shut-off valves, and also ramps up/down the mass flow controllers to obtain the desired gas flow rate. The process gas control instruction set **140** is invoked by the chamber manager instruction set **136**, as are all chamber component instruction sets, and receives process parameters related to the desired gas flow rates from the chamber manager **136**. Typically, the process gas control instruction set **140** operates by opening the gas supply, and repeatedly (i) reading the necessary mass flow controllers, (ii) comparing the readings to the desired flow rates received from the chamber manager instruction set **136**, and (iii) adjusting the flow rates of the gas supply lines as necessary. Furthermore, process gas control instruction set **140** includes steps for monitoring the gas flow rates for unsafe rates and activating the

safety shut-off valves when an unsafe condition is detected. Process gas control
instruction set **140** also controls the gas composition and flow rates for clean gases
as well as for etching of deposition gases, depending on the desired process (etching,
clean or deposition or other) that is selected. Alternative embodiments could have

5   more than one process gas control instruction set **140**, each instruction set controlling
a specific type of process or specific set of gas flow controllers.

In some processes, an inert gas such as nitrogen or argon is flowed into
chamber **28** to stabilize the pressure in the chamber before reactive process gases are

10   introduced. For these processes, the process gas control instruction set **140** is
programmed to include steps for flowing the inert gas into chamber **28** for an amount
of time necessary to stabilize the pressure in the chamber, and then the steps
described above would be carried out. Additionally, when a process gas is to be
vaporized from a liquid precursor, for example in the deposition of TEOS-derived glass,

15   process gas control instruction set **140** is written to include steps for bubbling a
delivery gas, such as helium, through the liquid precursor in a bubbler assembly, or for
introducing a carrier gas, such as helium, to a liquid injection system. When a bubbler
is used for this type of process, the process gas control instruction set **140** regulates
the flow of the delivery gas, the pressure in the bubbler, and the bubbler temperature

20   in order to obtain the desired process gas flow rates. As discussed above, the desired
process gas flow rates are transferred to the process gas control instruction set **140**
as process parameters. Furthermore, the process gas control instruction set **140**
includes steps for obtaining the necessary delivery gas flow rate, bubbler pressure,
and bubbler temperature for the desired process gas flow rate by accessing a stored

25   table containing the necessary values for a given process gas flow rate. Once the
necessary values are obtained, the delivery gas flow rate, bubbler pressure, and
bubbler temperature are monitored, compared with the necessary values, and adjusted
accordingly.

30   The pressure control instruction set **142** comprises program code for
controlling the pressure in the chamber **28** by regulating the aperture size of the
throttle valve **44** in the exhaust system **42** of the chamber. The aperture size of the
throttle valve **44** is set to control the chamber pressure at a desired level in relation to
the total process gas flow, the size of the chamber **28**, and the pumping set-point

pressur for the exhaust system **42**. When the pressure control instruction set **142** is invoked, the desired or target pressure level is received as a parameter from the chamber manager instruction set **136**. The pressur control instruction set **142** measures the pressure in the chamber **28** by reading one or more conventional

5   pressure manometers connected to the chamber **28**, compares the measure value(s) with the target pressure, obtains PID (proportional, integral, and differential) values corresponding to the target pressure from a stored pressure table, and adjusts the throttle valve **44** according to the PID values obtained from the pressure table. Alternatively, the pressure control instruction set **142** can be written to open or close

10   the throttle valve **44** to a particular aperture size to regulate the pumping capacity in chamber **28** to the desired level.

    Optionally, the heater control instruction set **144** comprises program code for controlling the temperature of an optional heater element (not shown) used

15   to resistively heat the support **32** and substrate **20**. The heater control instruction set **144** is also invoked by the chamber manager instruction set **136** and receives a target, set-point, or temperature parameter. The heater control instruction set **144** measures the temperature by measuring voltage output of a thermocouple located in the support, comparing the measured temperature with the set-point temperature, and

20   increasing or decreasing current applied to the heating unit to obtain the set-point temperature. The temperature is obtained from the measured voltage by looking up the corresponding temperature in a stored conversion table or by calculating the temperature using a fourth-order polynomial. When an embedded loop is used to heat support, the heater control instruction set **144** gradually controls a ramp up/down of

25   current applied to the loop. Additionally, a built-in, fail-safe mode can be included to detect process safety compliance and to shut down operation of the heating unit if the process chamber **28** is not properly set up.

    The plasma control instruction set **146** comprises program code for

30   setting low and high-frequency RF power levels applied to the process electrodes **50**, **52** in the chamber **28**. Like the previously described chamber component instruction sets, the plasma control instruction set **146** is invoked by the chamber manager instruction set **136**. For embodiments including remote plasma generator **46**, the

plasma control instruction set **146** would also include program code for controlling a remote plasma generator (not shown).

The endpoint detection instruction set **148** comprises program code that

5   obtains the sample and reference signals from the signal analyzer and normalizes the property of the reflected radiation relative to the property of the radiation originating from the radiation source **58**, the properties comprising one or more of an intensity, phase or wavelength. The normalization method, i.e., dividing, subtracting, or multiplying the two signal properties is pre-programmed into the computer software.

10   In addition, the compensation factor for determining background radiation is also written as program code. The endpoint detection instruction set **148** further comprises program code for performing other functions, such as detecting the endpoint of the process being performed on the substrate **20** based on a predetermined method of evaluating the normalized sample signal and sending

15   instructions to the chamber manager instruction set **136** or other instruction sets to change the process or other chamber conditions.

<u>EXAMPLE</u>

The following example illustrates the operation and superior results

20   obtained through use of the present invention. The apparatus used is essentially that depicted in Figure 1, and is a Model Si ETCH DPS available from Applied Materials, Santa Clara, California. A blank silicon wafer was loaded into the process chamber. The source mercury discharge lamp and the sample and reference detectors were

25   turned on. The source mercury discharge lamp was a Model CPG-1, available from Jelight Co. of Irvine, California; and the sample and reference detectors (photomultipliers, Hamamatsu Model R728). Either optical bandpass filters or monochromators were used to select the mercury emission at about 254 nm. The radiation transmitting fiber was used to transmit light from the lamp to the reference

30   detector and the process chamber, and from the process chamber to the sample detector. A sample signal (X_0) and reference signal (Y_0) were acquired before igniting a plasma.

A plasma was ignited at 600W power for a process gas comprising SF_6 introduced into the chamber. Two detectors were used to simultaneously acquir the reference (Y) and sample (X) signals. The signals were transmitted to the signal analyzing computer, namely the Centura Endpoint Computer, available from Applied

5 Materials, Santa Clara, California. The computer calculated the correction factor from the expression $C = X_0 / X_1$, and calculated the corrected sample signal using the expression $X_{mt} = X_t / \{Y_0 + C(Y_t - Y_0)\}$. A plot of the signals from 10 to 20 seconds is shown in Figure 4, where trace a is the sample signal, trace b is the reference signal and trace c is the corrected signal.

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In this example, the apparatus and methods of the present invention (without background correction) achieved a 10 fold (1000%) improvement in the signal-to-noise ratio of the sample signal. The apparatus and methods of the present invention (with background correction, signal c) achieved a 40 fold (4000%)

15 improvement in the signal-to-noise ratio of the sample signal.

Since a blank wafer was used in this experiment, the signal c in Figure 4 is featureless and smooth. In actual use, a wafer being etched would produce a time varying signal which, with the present invention, can be of small amplitude and still be

20 readily detectable.

The present invention has been illustrated by way of an exemplary plasma etching process, however, other versions are possible. For example, the monitoring process and apparatus can be used for other processes and in other

25 chambers as would be apparent to one of ordinary skill, including without limitation, sputtering chambers, ion implantation chambers and other deposition chambers. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

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